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Experimental Study and Design on Automobile Suspension Made of Magneto-Rheological Damper

Fengchen Tu*, Quan Yang, Caichun He, Lida Wang

ZhuZhou Times New Materials Science and Technology Co.Ltd, ZhuZhou, 412007, China

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Abstract

Magneto-rheological (MR) damper is an intelligent damper, which is used as automobile suspension for vibration semi-active control. A single piston rod MR damper with an accumulator was designed in order to satisfy with the demand of a certain automobile front suspension. The damper structural parameters were obtained by integrated optimal design combining magnetic circuit and structure. Magnetic circuit was analyzed by means of finite element method. The calculating formula derivation of damping force of MR damper with an accumulator was also achieved. Then the properties of designed damper were investigated by experiments, and the relationship between damping force, circuit and speed was fitted by the experimental results. This work provided promising method for the experimental study and design on automobile suspension made of MR damper.

Key words: automobile suspension; MR damper; magnetic circuit analysis; damper properties

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1. Introduction

The properties of automobile suspension mostly influence the vehicle ride quality (ride comfort) and safety (operation stability). At present, the widely used hydraulic mount is incapable of real-time performance adjustment based on road situation and vehicle operation estate. Therefore, it is urgently to develop an intelligent automobile suspension which is capable of real-time performance adjustment.

MR damper is becoming the most promising vibration controller in the intelligent suspension presently and it wins the favors of vehicle manufactures, because it takes the advantageous of high strength, good controllability, wide dynamic range, fast response rate, low energy consumption and simple structure. Now American LORD and Delphi companies have developed automobile suspension MR damper and it has been used in Cardilac and Audi some top-grade cars. Chinese car manufactures also have paid much attention to intelligent suspension and taken an active part in research on the technology and production. Moreover, with the increasing requirement of vehicle ride comfortable and safety, intelligent suspension

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* author: Fengchen Tu. Tel: +8673122837894. *Email address*：tufengchen@yahoo.cn

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will be widely adopted in normal cars and engineering automobile, consequently, it will bring broad market of automobile suspension made of MR damper.

The design of automobile suspension made of MR damper includes magnetic circuit design and structure design. The modification of MR damper based on experiments results and distinguish for model parameters also should be included in the design process. Our team designed the automobile front suspension by MR damper for a certain type, the work based on normal method and it integrated the special damper demand of automobile suspension. Meanwhile, the properties were tested and analyzed in our work.

2. Automobile front suspension design by MR damper

According to the analysis results of kinetics, parameters of a certain automobile front suspension MR damper were got as follows: the maximum damping force is 1500N, straight distance is 150mm, adjustable ratio of damping force (the ratio of adjustable damping force and un-adjustable damping force which is adjusted by magnetic field intensity) is above 4.5, and then MR damper was designed by these parameters.

2.1. Integrate optimal design of magnetic circuit and structure

Magnetic circuit parameter and structure parameter act or react on each other. Usually they are needed to be calibrated repeatedly. As a result, numerical optimization method was adopted to improve design efficiency instead of the former. Some factors as follows were considered in optimization:

- In the optimization of magnetic circuit system structure parameter of all parts, make sure the whole volume of damper is as small as possible, the weight is low.
- Make sure that in the whole magnetic circuit, any of magnetic saturation position will not restrain the further increase of whole magnetic field.
- Dynamic response rate of magnetic circuit should be as fast as possible.

The structure relating to magnetic field intensity in a gap filled with MR fluid is mainly piston and matched cylinder block, which consists of cylinder block gap. The object of optimal design and analysis of piston and cylinder block are half of axis of symmetry profile, because they are symmetric shapes. The specific parameters model of automobile suspension MR damper is showed in Fig.1. Radial dimension r_0、r_1、r_2、r_3、t and h present piston rod radius, axle shoulder height, magnetic core radius, cylinder block thickness and ring gas thickness respectively. And axial sizes of $L_1$and L_2 present lengths of ring gap and piston.

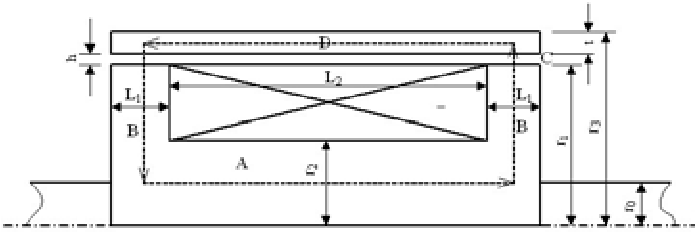


Fig.1. structure sketch and magnetic circuit diagram of MR damper main part

Relative magnetic permeability of MR fluid is a little bit higher than air (μ=1), while magnetic core and cylinder block are ferrimagnetic media, their relative permeability are above 10, that is μ>>10. Therefore, according to the fundamental properties of electromagnetic field, in the boundary of air and

MR fluid and piston and cylinder block, magnetic induction line was almost parallel to interface, magnetic lines of force leaked outside is little. The more magnetic permeability of piston always leads to obviously the phenomenon.

MR damper magnetic circuit was divided into A, B, C and D four parts as Fig.1 shows. For the reason that the size of ring gap was much smaller compared with the whole magnetic circuit, the magnetic flux of C is almost equal to each cross section in the magnetic circuit. So that the magnetic induction intensity relationship between gap C and piston and cylinder block was got. Magnetic induction intensity of C increased with the increase of magnetic permeability of piston and cylinder block.

Formula (1) is Ohm Law, which can be used to analyze the relationship of magnetic flux and magneto-motive force in the magnetic circuit and calculate the result of excitation current and magnetic induction intensity.

$$\phi = \frac{IN}{R_m} \tag{1}$$

Where, ϕ is magnetic flux in magnetic circuit;

IN is magneto-motive force of the whole magnetic circuit;

R_m is magneto-resistive of the whole magnetic circuit; $R_m = \frac{1}{\mu S}$, μ is magnetic permeability, S is cross section area of magnetic circuit.

Total magneto-resistive of close magnetic circuit is as follow:

$$R_m = 2\frac{h^2}{\left[\pi(r_1+h)^2 - \pi r_1^2\right]L_1\mu_0} + 2\frac{r_1}{\pi r_1 L_1 \mu} + \frac{L_1+L_2}{\pi r_2^2 \mu} + \frac{L_1+L_2}{\pi\left[r_3^2 - \left(r_1+h\right)^2\right]\mu} \tag{2}$$

Take the total magneto-resistive into Ohm Law, design calculation of each section of magnetic circuit was done by using the magnetic induction intensity formula $B_i = \mu_0\mu_i H_i$, where B_i, μ_i and H_i are relative magnetic induction intensity, magnetic permeability and magnetic field intensity of i section.

The following structural design optimal model building was obtained via magnetic circuit system model, calculation formulas of magnetic induction intensity and magnetic field intensity of each section, as well as dimension constraint and demand of dynamic response of damper.

$$\begin{cases} G(X) = \min\left(abs\left[B_C(X) - B_{Cs}\right]\right) \\ g_1(X) = B_A(X) - B_{As} < 0 \\ g_2(X) = B_B(X) - B_{Bs} < 0 \\ g_3(X) = B_D(X) - B_{Ds} < 0 \\ g_4(X) = T_{UP}(X) - T_t < 0 \\ g_5(X) = EX - F < 0 \end{cases} \tag{3}$$

In which, X is design variables of structural parameters; $X = \left[x_1, x_2, x_3 \cdots\right]^T = \left[r_0, r_1, r_2 \cdots\right]^T$

$B_C(\cdot)$ is magnetic induction intensity of C presented by design variables;

$B_A(\cdot)$ is magnetic induction intensity of A presented by design variables;

$B_B(\cdot)$ is magnetic induction intensity of B presented by design variables;

$B_D(\cdot)$ is magnetic induction intensity of D presented by design variables;

B_{Cs} is saturate magnetic induction intensity of MR fluid;

B_{As} 、 B_{Bs} and B_{Ds} are saturate magnetic induction intensity of A, B and D;

T_{UP} is response time of coils;

E and F are coefficient matrixes relating to damper structural parameter.

MR fluid damper structural parameters were obtained and showed in Tab.1, which was got by the means of MR fluid optimal design model and using MATLAB software to work out computer program.

Tab.1. Structural parameters of MR fluid damper

r_0/mm	r_1/mm	r_2/mm	r_3/mm	L_1/mm	L_2/mm	h/mm	t/mm
5.0	18.0	9.0	22.7	7.0	38.0	0.5	4.0

2.2. Magnetic circuit analysis

According to the foregoing structural parameters we got, magnetic field of magnetic circuit was analyzed using ANSYS finite elemental software. Magnetic circuit model building was got in the ANSYS finite elemental software, just one plane model was built because of axisymmetric structures of magnetic circuit. Then quadrilateral mesh was divided and current density was loaded in coils, and around the magnetic circuit magnetic line parallel constraint was also loaded. The material of damper is 20# steel and its B-H curve was showed in Fig.2 (a), and B-H curve of MR fluid was showed in Fig.2 (b).

Basing on the calculation results of finite elemental, magnetic circuit analysis results showed in Fig.3 and Fig.4 were got. Fig.3 is magnetic induction intensity nephogram, as it can be seen the magnetic induction of magnetic core, flanking and cylinder block were less than 1.5 Tesla, they are all undersaturated. As a result, with the maximum current the whole magnetic circuit will not be saturated, that is the damper has reasonable design.

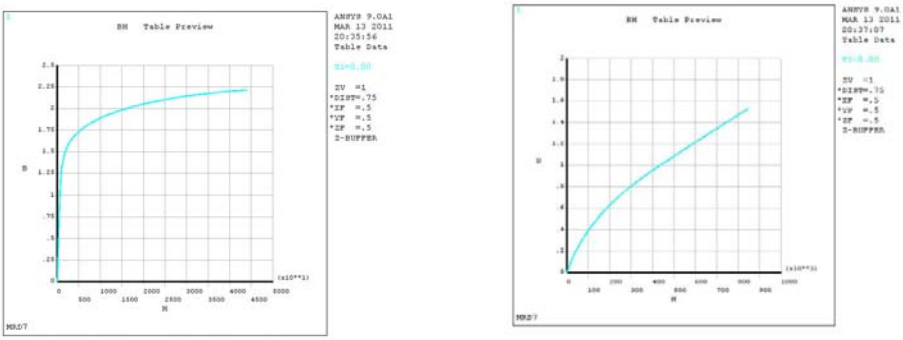


Fig.2 (a)20# steel B-H curves of materials (b) MR fluid B-H curves of materials

Under the maximum current, the magnetic induction intensity of ring gap was about 0.3 Tesla, at this moment shear yield strength of MR fluid was up to 30MPa and Coulomb damping force of MR damper reached the maximum.

Fig.4 is magnetic induction intensity nephogram of magnetic circuit, as it can be seen the whole magnetomotive force was loaded on the ring gap channel, while magnetomotive force of magnetic core, flanking and cylinder block were on the small side. So magnetic field utilization was high.

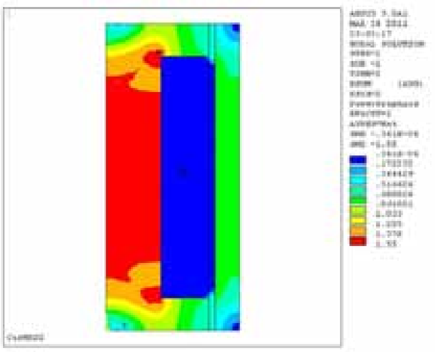


Fig.3. Magnetic induction intensity nephogram of magnetic circuit

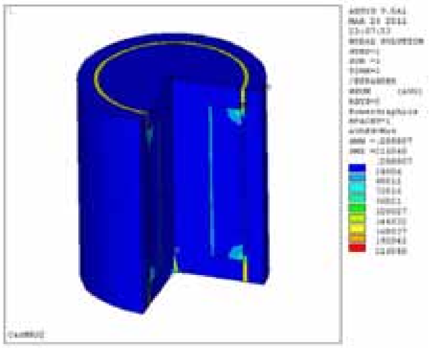


Fig.4. Magnetic field intensity nephogram of magnetic circuit

3. Energy storage cavity design and calculation

With same size, the stroke of fluid viscous dampers is less than single piston rod. Therefore, this single piston rod damper has obvious comparative advantage used in space-limited cars, but technical energy storage cavity need to be designed to fit the changeable volume of cylinder block as piston is moving. So energy storage cavity is essential in the single piston rod damper design progress.

3.1. Resistance of single piston rod damper

The floating piston, in which some gas was closed, it consists the energy storage cavity of single piston rod damper. The pressure of MR fluid increased when piston rod moved into cylinder block, which led to force imbalance between upper and lower surfaces of floating piston, then the downslide occurred. The floating piston had up-and-down movement as piston rod in and out of the cylinder block, which played a significant role in volume compensation. Meanwhile, piston downslide induced the decrease of MR fluid pressure and the increase of energy storage cavity resistance. Consequently, piston was in a balance in another position.

Indention of single piston rod MR damper was analyzed, then resistance formula was deduced. The piston that all piston rod exserted was set as the zero position of piston rod displacement (*x*). Friction between floating piston and cylinder block surface was ignored. Floating piston and main piston were chose to be as research object and force balance formula was established. Relation of resistance (*F*) and displacement (*x*) and initial pressure of energy storage cavity (p_0) in the compression process of damper were deduced and showed as follow:

$$F = \frac{P_{c0}\pi d^2}{4} + \frac{d^4}{D^4}kx + \frac{(P_c - P_e)\pi(D^2 - d^2)}{4} \tag{4}$$

Where, F is resistance of damper；

P_{c0} is internal pressure of MR fluid when main piston was in zero position;

P_c and P_e were lower chamber and upper chamber pressures of damper;

d is main piston diameter；

D is inner diameter of cylinder block;

k is energy storage cavity stiffness.

According to formula (4), it indicates: (1)The resistance of single piston rod MR damper with energy storage cavity includes three parts, the first part is initial resistance, which is proportional to initial internal pressure of MR fluid. The second part is restoring force of energy storage, and its value is proportional to stiffness of energy storage cavity. The two parts are uncontrollable resistance because they are not affected by the properties of magnetic field and MR fluid. The third part is MR fluid damping force, and its value is equal to viscous damping force under same condition with same structural parameter. (2)The higher initial pressure of energy storage, the lower adjustable ratio is. (3)When shear yield strength of MR fluid and speed of piston rod is constant, the adjustable resistance is also constant. Whereas, the total resistance will increase with the increase of piston rod displacement, also adjustable ratio of damper decreased gradually.

3.2. Energy storage design

The damper initial pressure was provided by high pressure energy storage cavity. If the maximum damping force beyond the provided pressure by energy storage cavity, MR fluid in the lower damper will push floating piston into slide, MR fluid in the lower damper doesn't pass ring gas to inpour into upper damper. With the increasing of compression, the damping force of MR fluid in the lower damper exceeds fluid resistance provided by main piston. Here the damping force was provided by energy storage cavity. And then the lower damper MR fluid passes the ring gap and inpour into upper damper. In the compression progress the energy storage cavity contractive volume is bigger than cylinder block compression volume. In hence, damping force hysteresis caused by spacing of upper damper is desirably avoidable. In order to conquer this problem, make sure the initial pressure (F_{c0}) provided by energy storage cavity is higher than the maximum damping force (F_{MRMax}).

$$F_{c0} = P_{c0} S_p \tag{5}$$

Where, S_p is a floating piston area;

$$F_{MRMax} = P_{1Max} S_p \tag{6}$$

Where, P_{1Max} is the maximum pressure of MR fluid in lower damper.

Formula (5) is equal to formula (6), and the critical equilibrium of floating piston was developed as follows:

$$P_{c0} = \frac{P_{1Max} S_p}{S_p} \tag{7}$$

on the Basis of structural parameters in Tab.1, calculation results showed that the minimum initial pressure of energy storage cavity is $P_{1Max} = F_{\max} / S_p = 1500/1027 \approx 1.5\text{MPa}$ 。 That means when the piston is all out, there are more than 1.5MPa high pressure nitrogen should be filled in the piston energy storage cavity.

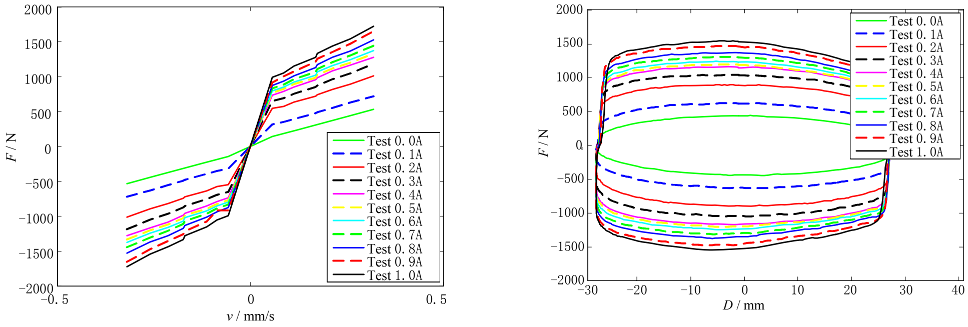
4. Experimental study

4.1. Performance test

The MR damper sample piece of vehicle suspension and experimental frock were processed based on the foregoing design parameters in our experiment, and showed in Fig.5. The damper performance, including force-displacement curve, force-speed curve and adjustable multiple and so on was tested by our fatigue testing machine.

Fig.5. (a) MR damper Sample Piece (b) Experiment Frock

Sine vibration, with the frequency of 1Hz、1.5Hz and 2.0Hz was provided by fatigue testing machine, and its vibration amplitude was 32mm. In different conditions, at the range from 0A to 1.0A direct current was inputted to MR damper. Experimental data was collected at intervals of 0.1A and the testing results were showed in Fig.6. In our experiments, offset force coming from energy storage cavity was removed during the data processing. As it can be seen, the MR damper showed obvious initial shear characters. With the increase of current and speed, the damping force was in an increase trend, however, it was not notable with the increase of current after 0.5A, instead a saturated performance was presented.



(a)Damping force and speed curve (b) Damping force and displacement curve

Fig.6. The measured performance curve of MR damper

4.2. The fitting relationship between damping force and current and speed

The relationship between damping force and current and speed of MR damper needed to be fitted for the vibration control and simulation analysis. According to the Bingham model, the relationship between them was presented as follows:

$$F = f_c \operatorname{sgn}(\dot{x}) + c_0 \dot{x} \tag{8}$$

In which: f_c is the relation term of damping force and current

c_0 ——viscous damping coefficient

Basing on our experiment data, cubic polynomial fitting was used to give the relation between f_c and variable current I, and the expression was given by least square method as follows:

$$f_c = c\tau_y = -632.2I^3 + 501.4I^2 + 868.1I \tag{9}$$

Viscous damping coefficient is $c_0 = 600$, and the correlative parameter of damper structure is $c = 0.0486$. In formula (9), I is loading current on damper ranging from 0A to 1A, x is loading displacement (mm), τ_y is shear yield strength.

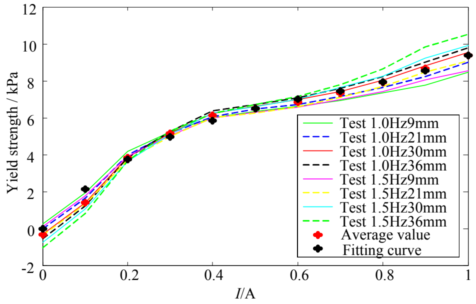
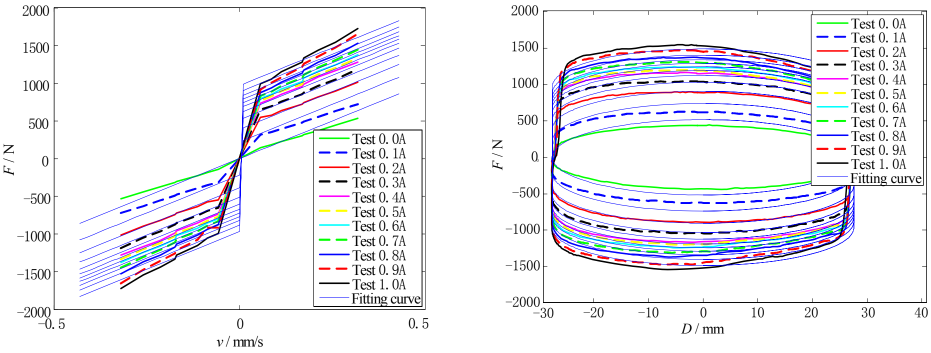


Fig.7. The comparison diagram of τ_y and I

Fig.7 shows the τ_y comparison diagram of fitting curve and tested experimental curve. The relation between the yield strength and current is stable and uniform. The increasing slope of yield strength increased in a small number with the increase of shear speed. The comparison diagram of fitted damper force-speed curve and the tested experimental curve was showed in Fig.8 (a). It presented that the viscosity of MRF wasn't constant and it increased with the increase of current. So there is a calculation error if the constant off state viscosity was used. There is a comparison between damper force and the displacement hysteresis curve in different condition. Fig.8 (b) was the comparison diagram of damping force-displacement hysteretic fitted curve and experimental curve in deferent condition. Generally, it was a better method to apply the fitting formula and parameter to present the relationship between damping force and current and speed, and with little error.



(a) damping force—speed curve (b) damping force—displacement curve

Fig.8. The comparison diagram of tested result and fitting result

5. Conclusion

- Magnetic circuit and structure integrated optimal design of MRF damper was well completed in our work. Multiple structure parameters and magnetic circuit parameters were simultaneously designed at the same time and it was with highly efficiency.
- The gas pressure in energy storage cavity directly affected the initial bias force, adjustable ratio and maximum resistance of damper. Therefore, the pressure value was needed to be absolutely ensured.

- Applying the least square method to fit the relationship between damping force and current and speed was a better way to describe the damper performance and with little error.

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